A New Technique for the Study of Charge Transfer in Multiply Charged Ion-Ion Collisions

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While large cross sections ($> 10^{-16}$ cm^2) have been predicted for resonant charge transfer in ion-ion collisions, no experimental data exist for multiply charged systems. A novel technique is being developed at the ORNL ECR facility to allow study of symmetric charge exchange in multiply charged ion-ion collisions using a single ion source. Specific intra-beam charge transfer collisions occurring in a well-defined interaction region labeled by negative high voltage are identified and analyzed by electrostatic analysis in combination with ion time-of-flight coincidence detection of the collision products. Center-of-mass collision energies from 400 to 1000 eV are obtained by varying source and labeling-cell voltages. In addition, by the introduction of a target gas into the high-voltage cell, this labeling-voltage method allows measurement of electron-capture and -loss cross sections for ion-atom collisions. Consequently, higher collision energies can be investigated without the requirement of placing the ECR source on a high-voltage platform.

Introduction

Basic processes in ion-atom collisions have been studied extensively over the last several decades. By comparison, little work has been done in the area of ion-ion collisions, especially for the case where both collision partners are multiply charged. Experimentally, this is due primarily to the difficulties (and expense) of producing merged or crossed multiply charged ion beams. Even so, Kim and Janev [1] have reported electron-loss cross sections for $Ar^{3+} + Ar^{3+}$ and $Kr^{3+} + Kr^{3+}$ collisions at 60 keV center-of-mass energy. In this case, electron loss (i.e., the production of an ion in the charge state q=4) was attributed to molecular Auger decay following the creation of inner-shell vacancies due to rotational coupling in the collisions. Charge transfer in these collisions was said to be insignificant. While the single-source folded-beam method employed in this measurement was certainly ingenious, its versatility to investigate other systems and processes is limited.

In addition to the obvious fundamental interest in ion-ion collisions, knowledge of these collision processes has applications in modeling the behavior of fusion plasmas and in understanding the dynamics of heavy-ion sources [2,3]. Very recently, symmetric charge transfer in multiply charged ion-ion collisions has been investigated theoretically by several groups [2,3,4]. To date, no experimental data exist for charge exchange in highly charged systems.

The cross sections for symmetric charge exchange, which is a resonant process, are predicted to be quite large ($> 10^{-16}$ cm^2). Shown in figure 1 are theoretical results for lithium-like ions from Tharamel, Kharchenko, and Dalgarno [4]. An interesting aspect of ion-ion charge transfer that differs from that for ion-atom collisions, is the energy threshold

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in the cross sections that is imposed by the Coulomb repulsion between the ions. For center-of-mass energies below threshold, the distance of closest approach is sufficiently large to render charge transfer improbable.

Here, we report on the development of a novel technique to permit study of symmetric charge exchange in multiply charged ion-ion collisions using a single ion source. In addition to these measurements which rely on the coincidence detection of both collision partners, this method allows non-coincidence measurement of electron-capture and -loss cross sections for ion-atom collisions by the introduction of a target gas into the interaction region. While these ion-atom measurements are intended primarily for diagnostic purposes, we present cross sections for projectile-electron loss in $He^+ + Ar$ collisions in an energy range previously unstudied.

Experimental design

The experimental apparatus and technique are being developed at the ECR highly charged ion source facility at Oak Ridge National Laboratory. The collision chamber and supporting beamline sit at the zero-degree port of the 90-degree analyzing magnet of the ECR source, as shown schematically in figure 2. With no magnetic dispersion of the ECR beam, all charge states of the beam extracted from the source enter the collision chamber. Impurity charge states in the beam resulting from charge exchange with residual gas in the beamline and from slit-edge scattering are deflected out of the beam by two sets of 63-degree electrostatic deflectors, shown schematically in figure 3. The beam then traverses a high-voltage "labeling cell," which is differentially pumped by a titanium-sublimation pump to insure the lowest pressure possible in this region. Subsequently, the beam is deflected by a 45-degree parallel-plate electrostatic analyzer and collected in a Faraday cup.

With the labeling cell held at negative high voltage, the ions are accelerated in the field entering the cell, acquiring a total kinetic energy $E = q(V_s + V_c)$, where q is the ion charge and V_s and V_c are the ECR source voltage and labeling-cell voltage, respectively. If no charge-changing collisions occur inside the cell, the ions are retarded in the field leaving the cell, having then a final energy equal to the initial energy of the ion from the source. $E = qV_s$. If, however, an ion undergoes a charge-changing event inside the cell, its final energy will be given by $E = q(V_s + V_c) - q'V_c$, where q' is the final charge of the ion. For single electron capture $q' = q - 1$, giving a final energy of $E = qV_s + V_c$, which is, importantly, higher than the initial kinetic energy of the ion, qV_s. Similarly for single electron loss, the final energy of the stripped ion is $qV_s - V_c$, which is lower than the initial energy of the ion. Table 1 illustrates the E/q values obtained for the case of Ar^{5+} and Ar^{6+} extracted from the ECR at a source voltage of 10 kV that undergo charge transfer in the labeling cell held at negative 20 kV.

Since the ions are dispersed in the parallel-plate analyzer according to E/q, a higher spatial separation between the charge-changed ions and the primary beam is achieved than if the collision had occurred at ground potential. Because of physical constraints of the apparatus, this greater separation is necessary in order to detect the ions. As illustrated in figure 3, detectors on both the high-energy and low-energy side of the Faraday cup can be positioned in order to detect ions that have undergone loss and capture to the particular

charge states of interest (according to E/q). Upon leaving the analyzer, the ions are deflected electrostatically onto chevroned microchannel plates which are positioned out of the analyzer plane to reduce detection of photons. The detectors are completely shielded to further reduce noise from detection of photons and electrons.

Because charge-changing collisions of the ions with the background gas in the labeling cell lead to identical E/q values as for ion-ion charge exchange, it is necessary to detect the ion-ion collision partners in coincidence. Since random coincidence detection of ions that have undergone loss and capture in the residual gas is proportional to the square of the pressure in the labeling cell, the lowest possible pressure in this region is desired in order to reduce noise. Even with the present working pressure of 2.5×10^{-10} Torr, a signal-to-noise rate on the order of 10% is expected.

In addition to increasing the dispersion of the charge-changed ions, the high-voltage labeling cell provides two other important functions: higher center-of-mass energies are obtained and the target length is well defined. Center-of-mass energies from approximately 400 to 1000 eV can be obtained by varying the source and labeling-cell voltages. The cross section for charge transfer, σ, can be determined by

$$\sigma = \frac{R}{I_1 I_2} \frac{v_1 v_2}{v_r} \frac{1}{lF}$$

where R is the ion-ion coincidence rate, I_1 and I_2 are the incident intensities of the two beams (i.e., charge states), v_1 and v_2 are the ion velocities in the lab frame, v_r the relative velocity, and l is the target length. F, the so-called form factor, is a measure of the spatial overlap of the beams. The form factor can be estimated from the modeled ion optics of the apparatus.

The incident intensities of the different charge states in the beam can be determined in two ways. Primarily, the charge-state distribution in the beam can be measured using the 90-degree analyzing magnet. In addition, the intensity of a particular charge state can be determined by comparing the detected singles rate with that expected from charge exchange with the background gas in the labeling cell. To this end, an ultrahigh-vacuum leak valve has been installed to allow for noble-gas targets, which are not pumped by the sublimation pump, to be introduced into the labeling-cell region.

By varying the target pressure, the cross section for charge exchange with the target gas can be determined by the well-known "initial growth method." Demonstrating this technique, we have measured the cross section for projectile-electron loss (stripping) for collisions of He^+ ions incident on Ar. The pressure was varied at each energy in the range of 10^{-10} to 8×10^{-7} Torr, and the collision energy was varied by changing both the source and the labeling cell voltages. The present results are shown in figure 4, along with earlier measurements performed at higher energies [5,6,7]. Since the energy dependence of the stripping cross section is very steep at these low energies, it is difficult to compare to the higher-energy results by extrapolation. However, a good agreement does appear to exist, allowing us to conclude that the labeling-voltage technique is working properly in this capacity. We must point out that these results are preliminary, and the uncertainty in the cross sections indicate only statistical errors and do not reflect any systematic errors inherent in the method.

In conclusion, while coincidence detection of ion-ion charge transfer has not yet been observed using the labeling-voltage method, further refinement of the technique is in progress. Additional measurements of charge exchange from target gases, with direct comparison to known cross sections, will allow for better characterization of the apparatus.

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References

[1] H.J. Kim and R.K. Janev, Phys. Rev. Lett. **58**, 1837 (1987).
[2] R.K. Janev and D.S. Belic, J. Phys. B: At. Mol. Phys. **15**, 3479 (1982).
[3] J.N. Bardsley, P. Gangopadhyay, and B.M. Penetrante, Phys. Rev. A **40**, 2742 (1989).
[4] J. Tharamel, V.A. Kharchenko, and A. Dalgarno, Phys. Rev. A **50**, 496 (1994).
[5] P.R. Jones, F.P. Ziemba, H.A. Moses, and E. Everhart, Phys. Rev. **113**, 182 (1959).
[6] M.B. Shah and H.B. Gilbody, J. Phys. B: At. Mol. Phys. **8**, 372 (1975).
[7] M.E. Rudd, T.V. Goffe, A. Itoh, and R.D. DuBois, Phys. Rev. A **32**, 829 (1985).

Table 1
Energy of Ar^{5+} and Ar^{6+} ions for a source voltage of 10 kV and a labeling-cell voltage of 20 kV for the case where no charge exchange occurs and for charge exchange.

Initial	Entering cell	Exiting cell	Final	E/q
50 keV Ar^{5+}	150 keV Ar^{5+}	150 keV Ar^{5+} (no exchange)	50 keV Ar^{5+}	10
60 keV Ar^{6+}	180 keV Ar^{6+}	180 keV Ar^{6+} (no exchange)	60 keV Ar^{5+}	10
		150 keV Ar^{6+} (exchange)	30 keV Ar^{6+}	5
		180 keV Ar^{5+} (exchange)	80 keV Ar^{5+}	16

Figure captions

Fig. 1. Theoretical cross sections for symmetric charge transfer in collisions of lithiumlike ions from Tharamel, Kharchenko, and Dalgarno [4].

Fig. 2. Schematic drawing showing the location of the ion-ion collisions experiment with respect to the ORNL ECR ion source.

Fig. 3. Schematic drawing of the experiment apparatus. The beam direction is from the bottom of the figure.

Fig. 4. Preliminary results for the cross section for projectile-electron loss in collisions of He^+ with Ar. Also shown are previous results from references [5,6,7].

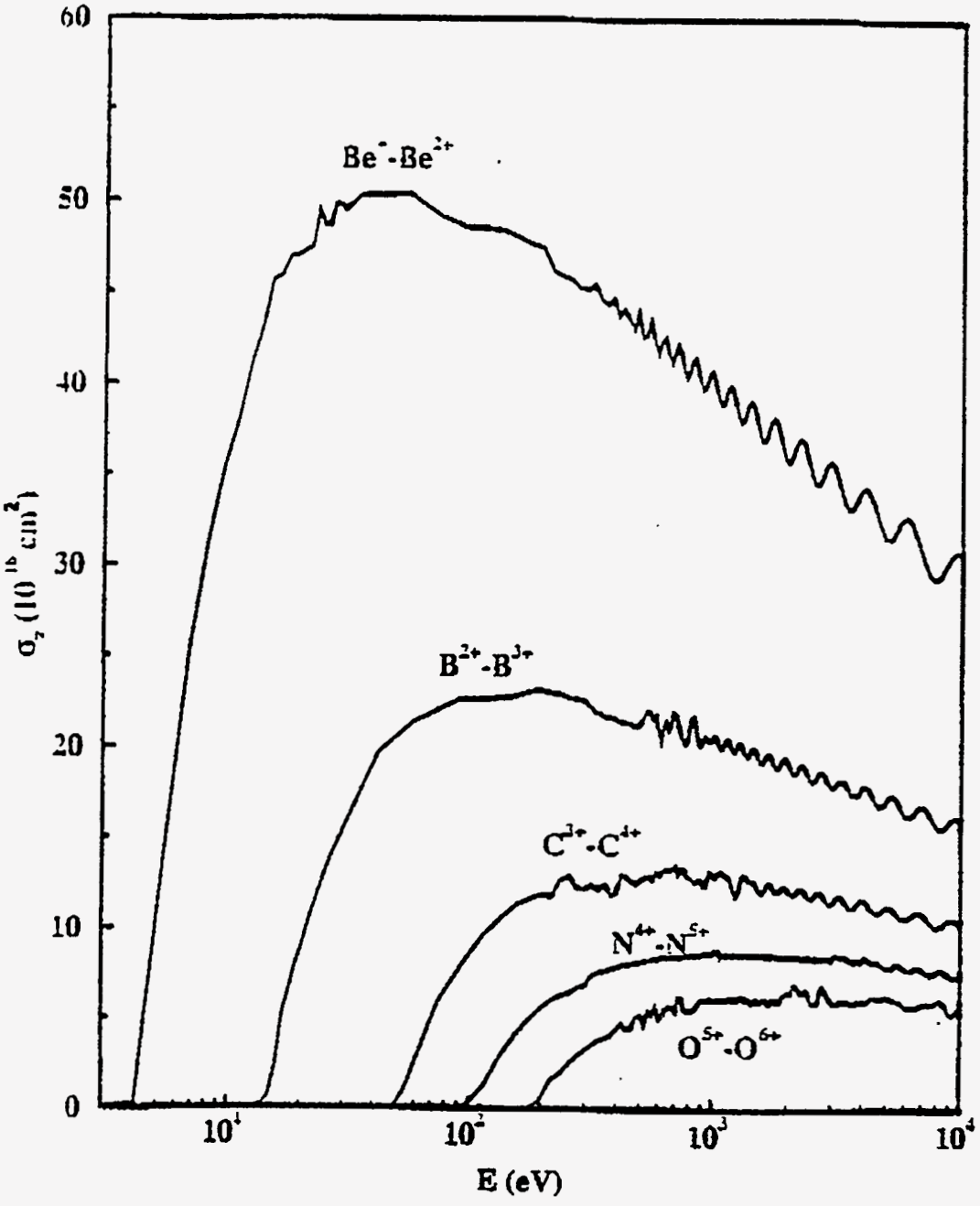
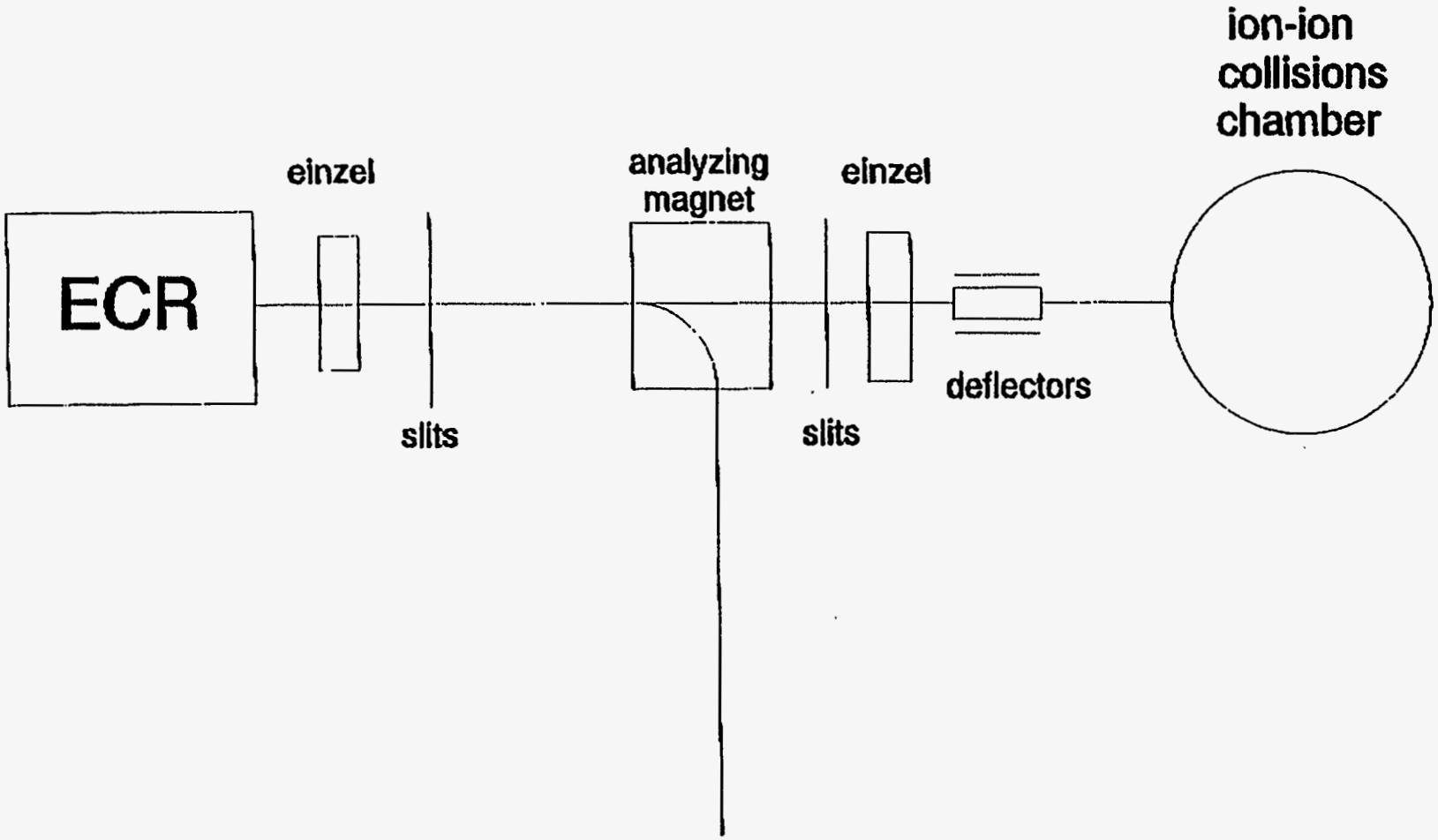

60
50
40
30
20
10
0
σ_z (10^{-16} cm^2)
Be^{+}-Be^{2+}
B^{2+}-B^{3+}
C^{3+}-C^{4+}
N^{4+}-N^{5+}
O^{5+}-O^{6+}
10^{1}
10^{2}
10^{3}
10^{4}
E (eV)

Fig. 1

Fig


ion-ion
collisions
chamber
einzel
analyzing
magnet
einzel
ECR
slits
slits
deflectors

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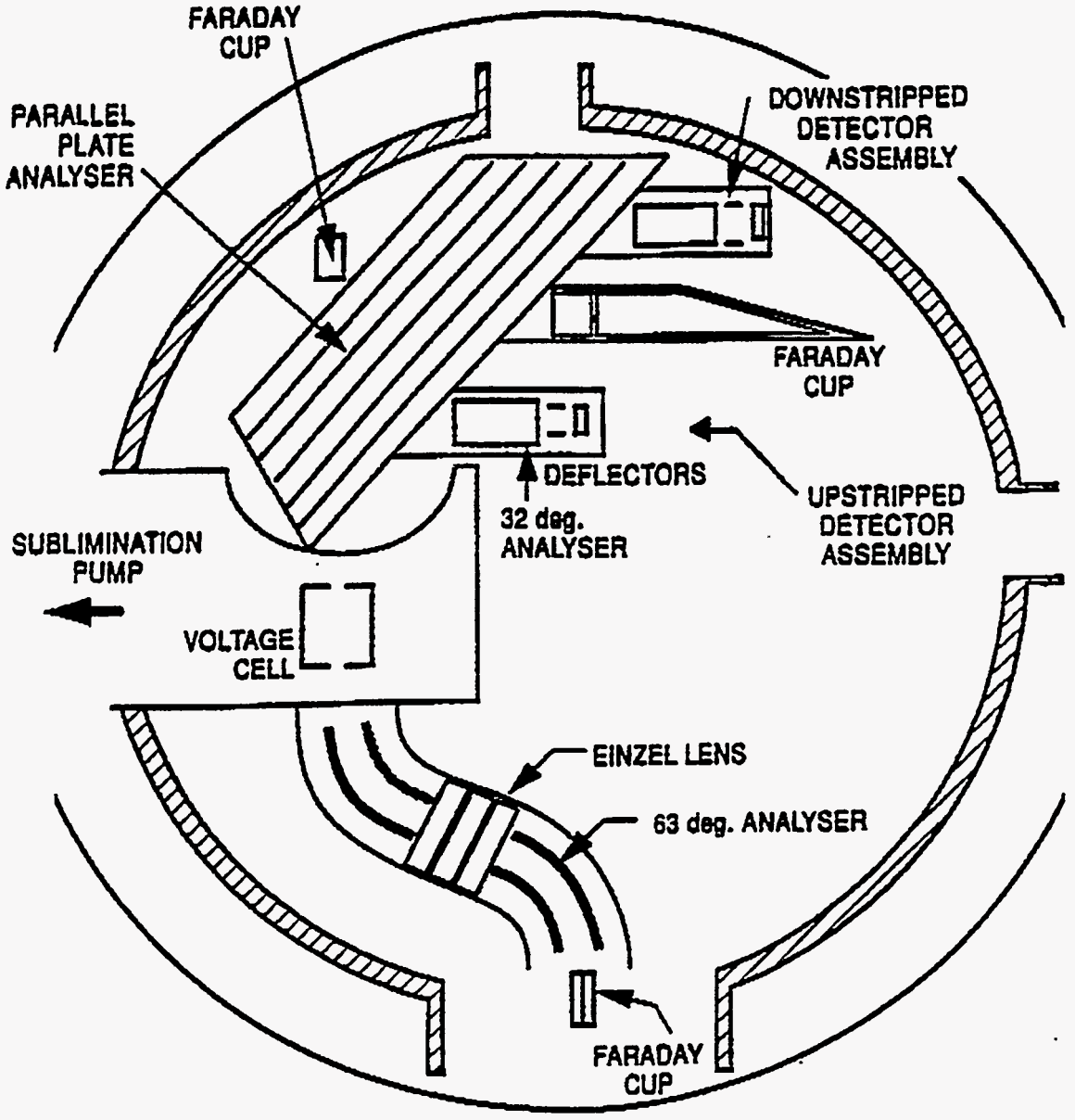
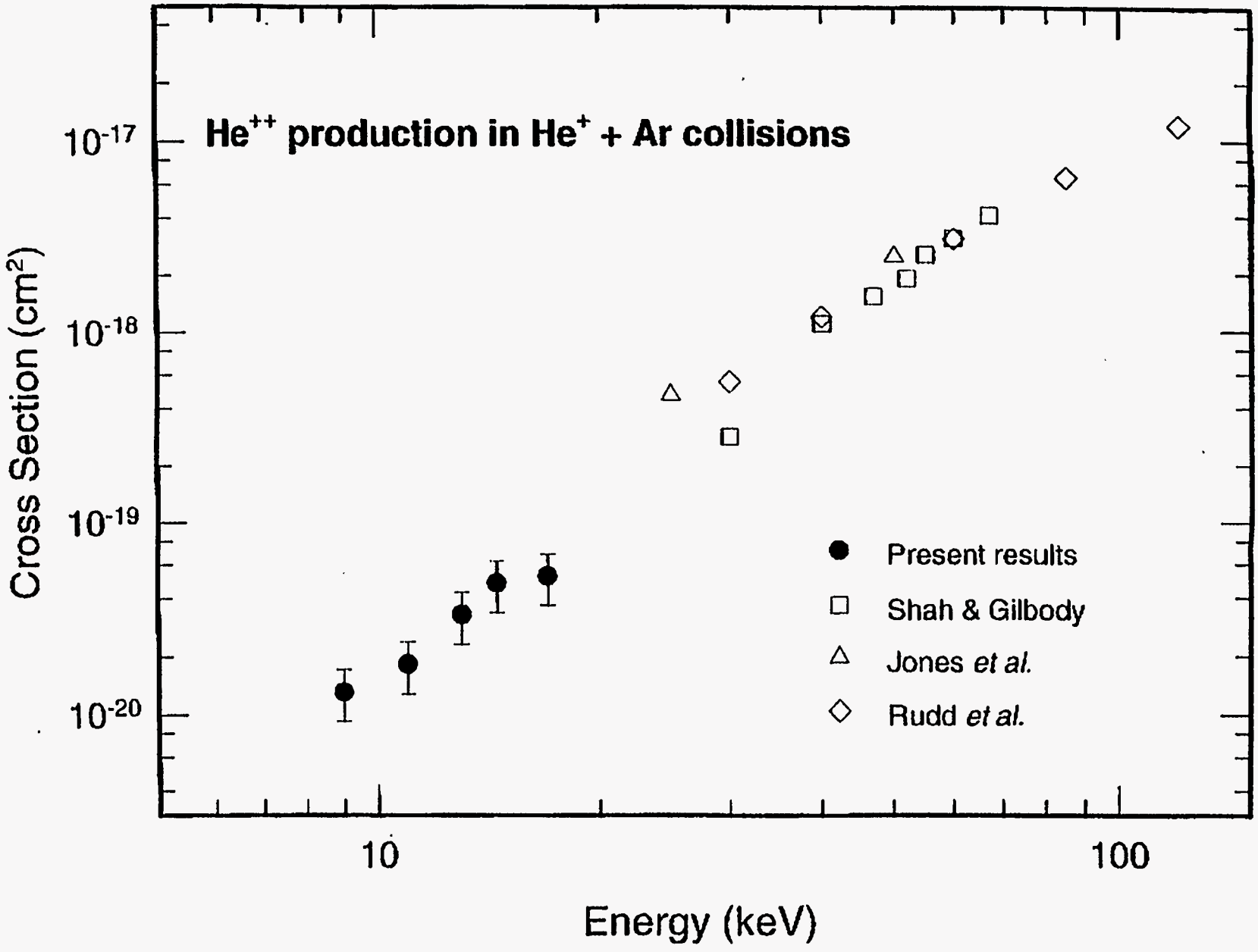


EXPERIMENTAL CHAMBER

Fig 4


He++ production in He+ + Ar collisions
Cross Section (cm2)
10-17
10-18
10-19
10-20
10
100
Energy (keV)
Present results
Shah & Gilbody
Jones et al.
Rudd et al.